Radiative Penguin and Leptonic Rare Decays at BABAR

Eugenio Paoloni
Dipartimento di Fisica dell'Università degli studi di Pisa
e
Istituto Nazionale di Fisica Nucleare, Sez. di Pisa
via Buonarroti 2, 56100 Pisa, Italy
(for the BABAR *collaboration)*

Recent BABAR results on rare B decays involving flavour-changing neutral currents or purely leptonic final states are presented. New measurements of the CP asymmetries in $B \to K^*\gamma$, $B \to K_2^*(1430)\gamma$, and $b \to s\gamma$ are reported, as well as a new measurement of the $B \to K^*\gamma$ branching fraction. Also reported are updated limits on $B \to \mu\nu$ and recent measurements of $B \to K^{(*)}\ell\ell$ and $b \to s\ell\ell$. The data sample comprises $123 \cdot 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected with the BABAR detector at the PEP-II e^+e^- storage ring.

Contributed to the Proceedings of the XXXIX Recontres de Moriond Electroweak Interactions and Unified Theories

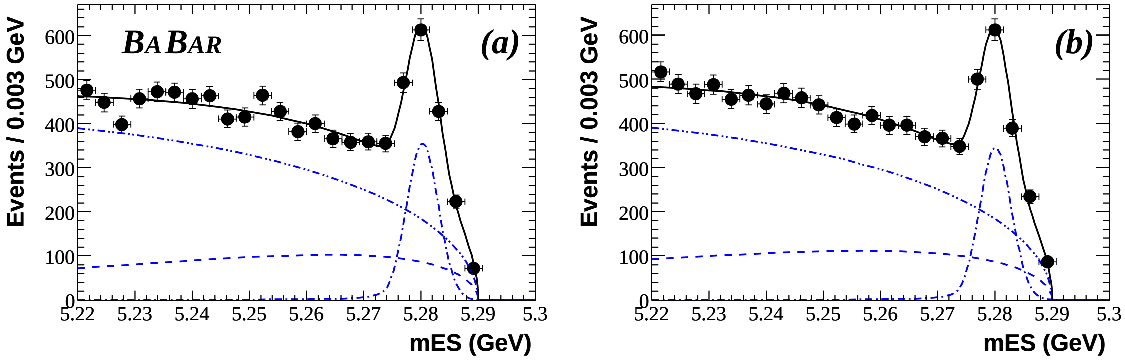


Figure 1: Fits to the beam–energy substituted mass distributions in data events for: (a) $\overline{B} \to X_s\gamma$, (b) $B \to X_{\overline{s}}\gamma$ Contributions are shown from peaking Crystal Ball (dotted–dashed), fixed continuum Argus shape (dotted) and free $B\overline{B}$ and cross–feed Argus shape (dashed).

1 Introduction

The study of radiative and leptonic rare B decays in search for significant discrepancies with respect to the Standard Model (SM) theoretical predictions represent a very attractive field of research. These decays can show some of the visible effects predicted by many extensions of the SM whose measure allows to constraint (if not potentially to discover) new physics.

The BABAR collaboration exploited the unprecedented PEP-II luminosity to perform an extensive and detailed series of studies on these decays analysing a sample that comprise $123 \cdot 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays recorded by the BABAR detector [1].

This paper will summarize the results of these searches.

2 CP violation in radiative B Decays

Radiative decays $b \to s\gamma$ proceed at leading order in the SM through one loop penguin diagrams. The new fields predicted by many extensions of the SM can contribute with additional amplitudes to this process appearing as virtual particles in the penguin loop diagrams. The comparison of the measured inclusive branching ratio (world average $\mathcal{B}.\mathcal{R}.(B \to X_s\gamma) = (3.3 \pm 0.4) \cdot 10^{-4}$ [2]) with respect to the SM theoretical predictions ($(3.6 \pm 0.3) \cdot 10^{-4}$ [3,4]) has already provided some constraints on the new physics beyond the SM [5].

The measurement of the CP violation can shed new light on the structure of this flavour changing neutral current both testing the SM predictions and constraining the space parameter of the SM extensions.

2.1 Direct CP violation in $\overline{B} \to X_s\gamma$ decays

In the SM the CP violation in the inclusive process $\overline{B} \to X_s\gamma$ can be reliably predicted [6]:

$$\mathcal{A}_{CP} = \frac{\Gamma\left(\overline{B} \to X_s\,\gamma\right)\; - \;\Gamma\left(B \to X_{\overline{s}}\,\gamma\right)}{\Gamma\left(\overline{B} \to X_s\,\gamma\right)\; + \;\Gamma\left(B \to X_{\overline{s}}\,\gamma\right)} \;=\; 0.0044^{+0.0024}_{-0.0014} \tag{1}$$

whereas in some Super Symmetric scenarios sizable asymmetries ($\mathcal{A}_{CP} \sim 10\%$) are possible and natural [7].

In this analysis [8] a sample of $(88.9 \pm 1.0) \times 10^6$ $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance is used. The $\overline{B} \to X_s\gamma$ sample is obtained combining the twelve full reconstructed self-tagging

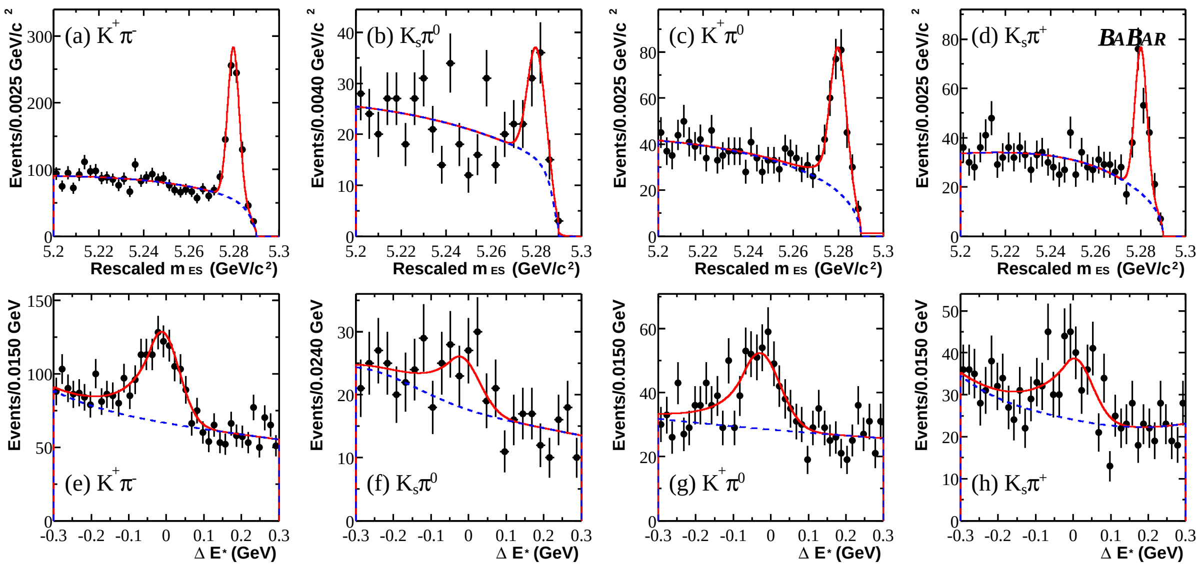


Figure 2: M_{ES} and ΔE^* distributions for the $B \to K^*\gamma$ candidates. The solid and dashed curves show respectively the projections of the complete fit and background component alone.

decay channels:

$$\begin{aligned} B^- \to &\quad K^-\pi^0\gamma, K^-\pi^+\pi^-\gamma, K^-\pi^0\pi^0\gamma, K^-\pi^+\pi^-\pi^0\gamma \\ \overline{B}^0 \to &K^-\pi^+\gamma, K^-\pi^+\pi^0\gamma, K^-\pi^+\pi^0\pi^0\gamma, K^-\pi^+\pi^-\pi^+\gamma \\ B^- \to &\; K^0_S\pi^-\gamma, K^0_S\pi^-\pi^0\gamma, K^0_S\pi^-\pi^0\pi^0\gamma, K^0_S\pi^-\pi^+\pi^-\gamma. \end{aligned}$$

Their charge conjugate is used to obtain the $B \to X_{\overline{s}}\gamma$ sample. Fully reconstructed $B \to X_{\overline{s}}\gamma$ decays are characterized by two kinematic variables: the beam–energy substituted mass, $m_{ES} = \sqrt{(\sqrt{s}/2)^2 - p_B^{*2}}$, and the energy difference between the B candidate and the beam–energy, $\Delta E = E_B^* - (\sqrt{s}/2)$, where E_B^* and p_B^* are the energy and momentum of the B candidate in the e^+e^- center–of–mass frame, and $\sqrt{s}$ is the total center–of–mass energy. We require candidates to have $|\Delta E| < 0.10$ GeV, and then we fit the m_{ES} distribution between 5.22 and 5.29 GeV to extract the signal yield. The positive identification of charged kaons removes any contribution from $b \to d\gamma$.

$\mathcal{A}_{CP}$ is obtained from the yield asymmetry between the B and the $\overline{B}$ sample correcting for flavour misidentification and detector asymmetry.

In Figure 1 the final fits to the m_{ES} distributions for $b \to s\gamma$ and $\overline{b} \to \overline{s}\gamma$ events are presented.

We measure an CP asymmetry of $(0.025 \pm 0.050 \pm 0.015)$, where the first errors is statistical and the second systematic, corresponding to an allowed range of $-0.06 < \mathcal{A}_{CP}(b \to s\gamma) < +0.11$ at 90% confidence level in good agreement with the SM predictions.

2.2 Search for CP or isospin asymmetries in the $B \to K^*\gamma$ decays

The set of exclusive decays $B \to K^*\gamma$ provide other opportunities to test the SM predictions for the isospin (Δ_{0-}, Eq. 2) and the CP asymmetries ($\mathcal{A}_{CP}$, Eq. 3):

$$\Delta_{0-} = \frac{\Gamma(\overline{B^0} \to \overline{K^{*0}}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\overline{B^0} \to \overline{K^{*0}}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}, \tag{2}$$

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}. \tag{3}$$

Table 1: $B \rightarrow K^*\gamma$ analysis: the results from the likelihood fit are summarized. The signal efficiency ϵ, the fitted signal yield N_S, the branching fractions $\mathcal{B}$and the CP-asymmetries $\mathcal{A}_{CP}$ for each decay mode are shown. The combined branching fractions for $B^0 \rightarrow K^{*0}\gamma$ or $B^+ \rightarrow K^{*+}\gamma$ are also shown. Errors are statistical and systematic, respectively, with the exception of ϵ and N_S where ϵ only has a systematic error N_S has only a statistical error.

Mode	$\epsilon(\%)$	N_S	$\mathcal{B} \times 10^{-5}$	combined $\mathcal{B} \times 10^{-5}$	$\mathcal{A}_{CP}$
$K^+\pi^-$	24.4±1.4	582.6±29.7	3.92±0.20±0.23	3.92±0.20±0.24	-0.069±0.046±0.011
$K_s\pi^0$	15.3±1.9	61.8±15.3	4.02±0.99±0.51		
$K^+\pi^0$	17.4±1.6	250.9±22.6	4.90±0.45±0.46	3.87±0.28±0.26	0.084±0.075±0.007
$K_s\pi^+$	22.1±1.4	156.9±15.7	3.52±0.35±0.22		0.061±0.092±0.006

The SM predicts a positive Δ_{0-} between 5 and 10% [9], and $\mathcal{A}_{CP}$ less than 1% [7]. New physics contributions can modify these values significantly.

This analysis uses a sample of $88.2 \times 10^6 B\overline{B}$. The K^* is reconstructed in the self-tagging decay channels $K^{*0} \rightarrow K^+\pi^-$; $K^{*+} \rightarrow K^+\pi^0$, $K^0_S\pi^+$ and their charge conjugates. For the isospin analysis was also used $K^{*0} \rightarrow K^0_S\pi^0$.

The signal yield and $\mathcal{A}_{CP}$ for each decay mode are reported in table 2.1, they are determined with a two-dimensional extended unbinned maximum likelihood fit to the m_{ES} and ΔE^*. Δ_{0-} is determined from the signal yields correcting for differences in signal efficiency and lifetime among the neutral and charged B. The preliminary results are:

$$\mathcal{A}_{CP} = -0.015 \pm 0.036\,(\text{stat.}) \pm 0.010\,(\text{sys.}) \tag{4}$$

$$\Delta_{0-} = +0.051 \pm 0.044\,(\text{stat.}) \pm 0.023\,(\text{sys.}) \pm 0.024\,(R^{+/0}) \tag{5}$$

the first being the statistical and the second the systematic error. The third error on Δ_{0-} is related to the uncertainty on the ratio of the branching ratios recently measured by the BABAR collaboration [10]:

$$R^{+/0} = \frac{\mathcal{B.R.}\,(\Upsilon(4S) \rightarrow B^0\overline{B}^0)}{\mathcal{B.R.}\,(\Upsilon(4S) \rightarrow B^+B^-)} = 1.006 \pm 0.048$$

and accounts for the possibility of different production rate of charged and neutral B.

2.3 Search for time dependent CP asymmetry in $B \rightarrow K^*\gamma\,(K^* \rightarrow K^0_S\pi^0)$

The final state $K^0_S\pi^0\gamma$ is accessible to both the B and the $\overline{B}$ through $K^0 - \overline{K}^0$ mixing:

$$B^0 \rightarrow \overline{K}^{*0}\gamma(\overline{K}^{*0} \rightarrow K^0_S\pi^0)$$
$$\overline{B}^0 \rightarrow K^{*0}\gamma(K^{*0} \rightarrow K^0_S\pi^0).$$

The interference between decay and mixing can produce a time dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0(t) \rightarrow K^0_S\pi^0\gamma) - \Gamma(\overline{B}^0(t) \rightarrow K^0_S\pi^0\gamma)}{\Gamma(B^0(t) \rightarrow K^0_S\pi^0\gamma) + \Gamma(\overline{B}^0(t) \rightarrow K^0_S\pi^0\gamma)} = S\,\sin\Delta m\,t\; - \;C$$

where t is the time elapsed since the B meson production, and C is the direct CP asymmetry measured in the analysis previously described. In the SM the helicity structure of the hadronic currents strongly suppress the time dependent CP asymmetry [11]:

$$S = 2\,\frac{m_s}{m_b}\,\sin 2\beta \sim 4\%\;,\;|C| < 1\%$$

We analyzed 124 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays selecting 1916 $B \rightarrow K^0_S\gamma$ candidates. The decay point of these candidates is obtained intersecting the K^0_S flight direction with the beams

line. The flavour and the decay point of the companion B is determined with an inclusive reconstruction [12]. The fit to $\mathcal{A}_{CP}(t)$ give the preliminary result [13]:

$$S = 0.25 \quad \pm 0.63 \pm 0.14$$
$$C = -0.57 \pm 0.32 \pm 0.09$$

where the first error is statistical and the second systematic.

2.4 Measurement of the $B \to K_2^*(1430)\gamma$ branching ratio

During the last year the BABAR collaboration analyzed 88.5×10^6 $B\overline{B}$ events to measure the $B \to K_2^*(1430)\gamma$ branching ratio [14]. The candidates are reconstructed in the decay channels:

$$\overline{B}^0 \to K_2^*(1430)^0\gamma \quad (K_2^{*0} \to K^+\pi^-)$$
$$B^+ \to K_2^*(1430)^+\gamma \quad (K_2^{*+} \to K^+\pi^0, K_S^0\pi^+)$$

It is interesting to note that the most dangerous background in this analysis is represented by other rare $B \to X_s\gamma$ modes (mainly $B \to K^*(1410)\gamma$). The $K_2^*(1430)$ is a $J^P = 2^+$ resonance whereas the $K^*(1410)$ has $J^P = 1^-$ then the distribution of the helicity angle ϑ_H of the kaon in the K^* rest frame does differ for signal and background. We measure the signal yield with a multidimensional fit to $\cos\vartheta_H$, the energy substituted mass m_{ES}, and the center-of-mass frame energy difference ΔE. The preliminary measurement of the branching fractions are:

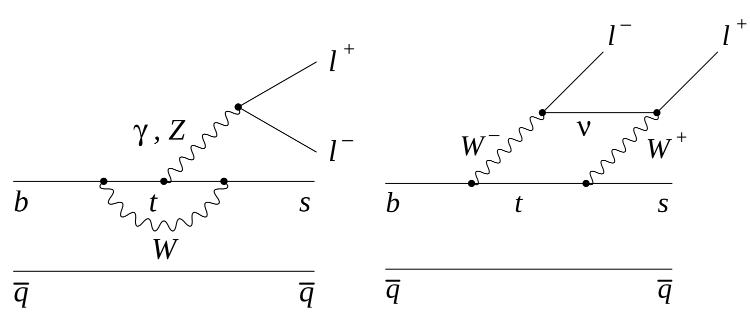
$$\mathcal{B.R.}\big(\overline{B}^0 \to K_2^*(1430)^0\gamma\big) = (1.22 \pm 0.25 \pm 0.11) \times 10^{-5}$$
$$\mathcal{B.R.}\big(B^+ \to K_2^*(1430)^+\gamma\big) = (1.44 \pm 0.40 \pm 0.13) \times 10^{-5}$$

in good agreement with the SM theoretical prediction [15]:

$$\mathcal{B.R.}\big(B \to K_2^*(1430)\gamma\big) = (1.48 \pm 0.30) \times 10^{-5}.$$

3 Measurement of $b \to s\ell^+\ell^-$ branching fractions

The process $b \to s\ell^+\ell^-$ is another very promising field of research. With respect to the $b \to s\gamma$ decays there are two additional diagrams contributing to the process: a penguin diagram with a Z^0 insertion and a box diagram:



Since the last year the BABAR collaboration finalized on $113\,\mathrm{fb}^{-1}$ [16] the measurement of the branching ratios $B \to K^{(*)}\ell^+\ell^-$.

$$\mathcal{B.R.}\big(B \to K\ell^+\ell^-\big) = \big(6.5^{+1.4}_{-1.3} \pm 0.4\big) \times 10^{-7}$$
$$\mathcal{B.R.}\big(B \to K^*\ell^+\ell^-\big) = \big(8.8^{+3.3}_{-2.9} \pm 1.0\big) \times 10^{-7},$$

and performed a preliminary measurement of the inclusive branching ratio $B \to X_s\ell^+\ell^-$ using a sum over exclusive modes in which X_s is composed by one kaon, one charged pion and/or one neutral pion [17]:

$$\mathcal{B.R.}\left(B \to X_s\ell^+\ell^-\right) = \left(6.3 \pm 1.6^{+1.8}_{-2.5}\right) \times 10^{-6}.$$

All these results are in good agreement with the SM theoretical predictions.

4 Leptonic B decays

The study of the purely leptonic $B^+ \to \ell^+\nu_\ell$ can provide sensitivity to poorly constrained SM parameters and also act as a probe for new physics. In the SM the reaction proceed through $\bar{b}u \to W^+ \to \ell^+\nu_\ell$ and the branching ratio is given by:

$$\mathcal{B.R.}(B^+ \to \ell^+\nu) = \frac{G_F^2\, m_B\, m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B\, |V_{ub}|^2\, \tau_B,$$

where G_F is the Fermi coupling constant, m_ℓ and m_B are the lepton and meson masses, f_B is the B decay constant, V_{ub} is the relevant CKM matrix element and τ_B is the $B+$ lifetime. Currently the f_B parameter comes from lattice QCD simulation and is affected by a 15% uncertainty. Observation of $B^+ \to \ell^+\nu_\ell$ could provide the first direct measurement of f_B. Unfortunately leptonic decays are strongly suppressed by helicity and there are not yet experimental evidence for such decays. Using 88.4 million $B\overline{B}$ events BABAR set an upper limit on the branching ratio

$$\mathcal{B.R.}(B^+ \to \mu^+\nu_\mu) < 6.6 \cdot 10^{-6}$$

at the 90% confidence level. This limit is consistent with the SM predictions.

5 Conclusions

The unprecedented luminosity of the B-factories permitted to perform new extensive and detailed tests on the processes $b \to s\gamma$ and $b \to s\ell^+\ell^-$ involving flavour changing neutral currents. There are no experimental evidences of *CP* violation in the $b \to s\gamma$ at the 5% level and the SM predictions are confirmed. Both BABAR and Belle are collecting a richer data sample that will consent more stringent tests of these aspect of the SM and eventually bring in a near future some surprises.

References

1. B. Aubert et al. The babar detector. Nucl. Instrum. Meth., A479:1–116, 2002, hep-ex/0105044.
2. K. Hagiwara et al. Review of particle physics. Phys. Rev., D66:010001, 2002.
3. Paolo Gambino and Mikolaj Misiak. Quark mass effects in $\overline{B} \to X_s\gamma$. Nucl. Phys., B611:338–366, 2001, hep-ph/0104034.
4. Andrzej J. Buras, Andrzej Czarnecki, Mikolaj Misiak, and Jorg Urban. Completing the NLO QCD calculation of $\overline{B} \to X_s\gamma$. Nucl. Phys., B631:219–238, 2002, hep-ph/0203135.
5. Tobias Hurth. Present status of inclusive rare B decays. Rev. Mod. Phys., 75:1159–1199, 2003, hep-ph/0212304.
6. T. Hurth, E. Lunghi, and W. Porod. Updated NLL results for $\overline{B} \to X_{s,d}\gamma$ in and beyond the SM. 2003, hep-ph/0310282.
7. Alexander L. Kagan and Matthias Neubert. Direct *CP* violation in $B \to X_s\gamma$ decays as a signature of new physics. Phys. Rev., D58:094012, 1998, hep-ph/9803368.

8. B. Aubert et al. Measurement of the direct CP asymmetry in $b \to s\gamma$ decays. 2004, hep-ex/0403035.
9. Alexander L. Kagan and Matthias Neubert. Isospin breaking in $B \to K^*\gamma$ decays. Phys. Lett., B539:227–234, 2002, hep-ph/0110078.
10. B. Aubert et al. Measurement of the B^+/Bz production ratio from the upsilon(4s) meson using $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^0_S$ decays. Phys. Rev., D69:071101, 2004, hep-ex/0401028.
11. David Atwood, Michael Gronau, and Amarjit Soni. Mixing-induced *CP* asymmetries in radiative B decays in and beyond the standard model. Phys. Rev. Lett., 79:185–188, 1997, hep-ph/9704272.
12. B. Aubert et al. A study of time dependent *CP*-violating asymmetries and flavor oscillations in neutral b decays at the Upsilon(4S). Phys. Rev., D66:032003, 2002, hep-ex/0201020.
13. B. Aubert et al. Measurement of time-dependent *CP*-violating asymmetries in $B^0 \to K^{*0}\gamma\,(K^{*0} \to K^0_S\pi^0)$ decays. 2004, hep-ex/0405082.
14. B. Aubert et al. Measurement of the $B^0 \to K_2^*(1430)^0\gamma$ and $B^+ \to K_2^*(1430)^+\gamma$ branching fractions. 2003, hep-ex/0308021.
15. Hai-Yang Cheng and Chun-Khiang Chua. Covariant light-front approach for $B \to K^*\gamma, K(1)\gamma, K^*(2)\gamma$ decays. Phys. Rev., D69:094007, 2004, hep-ph/0401141.
16. B. Aubert et al. Evidence for the rare decay $B \to K^*\ell^+\ell^-$ and measurement of the $B \to K\ell^+\ell^-$ branching fraction. Phys. Rev. Lett., 91:221802, 2003, hep-ex/0308042.
17. B. Aubert et al. Measurement of the $B \to X_s\ell^+\ell^-$ branching fraction using a sum over exclusive modes. 2003, hep-ex/0308016.